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Keywords: Efficient Lighting, Voltage Fluctuations, Flicker, Power Quality, Complexity.

Experimental Study of the Response of Efficient Lighting Technologies to Complex Voltage Fluctuations.

I. Azcarate[*,a], J.J. Gutierrez[a], A. Lazkano[a], P. Saiz[a], K. Redondo[a], L.A. Leturiondo[a]

Affiliations and addresses:

[a] Communications Engineering Department.
University of the Basque Country UPV/EHU.
Alameda Urquijo S/N
48013 Bilbao, Spain

Corresponding author:

[*] Izaskun Azcarate
email: izaskun.azkarate@ehu.es
Tel. : +34946018209
Fax. : +34946014259

Abstract

The replacement of incandescent lamps with more energy-efficient lighting technologies has a direct influence on the way flicker is measured. The International Electrotechnical Commission (IEC) established in the 61000-4-15 standard the functional specifications of a flickermeter, taking a standard incandescent lamp's response to voltage fluctuations as the reference. During the past ten years, different works have studied the sensitivity of modern lamps to analytical voltage fluctuations of low complexity. From these studies, the most widespread conclusion is that modern lamps are less sensitive to flicker than are incandescent lamps. Based on these results, international standardization organizations are currently studying two different possibilities for updating the flicker assessment procedure: adjusting the IEC flickermeter according to a new less sensitive reference lamp, or increasing the established compatibility levels for voltage fluctuations. This work presents for the first time a sensitivity analysis of a set of modern lamps subjected to real voltage signals that are more complex than analytical voltage fluctuations. The obtained results lead to the following conclusions: not all efficient lamps have a lower sensitivity to fluctuations than do incandescent lamps; the response of some lamps depends on the complexity of the input voltage fluctuation; and the response of some lamps in real scenarios, i.e., more complex voltage fluctuations, does not correlate with their response to simple voltage fluctuations.

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1. Introduction

International regulations have prompted the mass replacement of incandescent lamps with energy-efficient lighting technologies. There is a rising concern over the relationship between the large-scale introduction of such lamps and the Power Quality [1–3]. In this sense, the way flicker is measured now takes special relevance [4]. Flicker is defined as the irritation suffered by humans when exposed to illuminance fluctuations produced by changes in the supply voltage. The standard IEC 61000-4-15 [5], whose predecessor was IEC 868 [6], establishes the functional specifications for a flickermeter—a device that objectively quantifies the level of irritation by using the short-term (10 min) and long-term (2 hours) flicker severity, P_{st} and P_{lt}, respectively. The specifications and reference values, detailed in the standard from its first publication in 1986, were based on the leading lighting technology at that time: the 60 W incandescent lamp. Compatibility levels for voltage fluctuations were specified based on the assumption that a value of $P_{\mathrm{st}} = 1$ would lead to complaints from at least 50% of the people exposed to the light fluctuation produced by an incandescent lamp.

The gain curve is traditionally used to characterize the sensitivity of lamps subjected to sinusoidal voltage fluctuations. This method calculates the relationship between the relative amplitudes of the illuminance and voltage fluctuations for a given fluctuation frequency. Modern lamps' gain curves are generally lower than those of incandescent lamps, so new lighting technologies are considered significantly less sensitive to voltage fluctuations [7, 8]. Taking into account the progressive replacement of incandescent lamps and assuming the lower sensitivity of energy-efficient lighting technologies to voltage fluctuations, international organizations for the standardization and improvement of electric power systems are currently studying alternative flicker measurement protocols adapted to current technologies: for instance, adjusting the IEC flickermeter according to a new, modern reference lamp, or increasing the established compatibility levels for voltage fluctuations [9].

The specifications of the IEC flickermeter use the gain curve of an incandescent lamp as a linear model, combined with the human eye's response to light fluctuations. The IEC flickermeter's behavior is thus always linear, irrespective of the complexity of voltage fluctuations. However, it has not been demonstrated that this mirrors the behavior of modern lighting technologies [10, 11]. The current work analyzes the behavior of modern lamps with complex voltage supplies, such as rectangular analytical fluctuations and real voltage signals. The main objective was to study whether their gain curves, which were obtained from simple sinusoidal fluctuations, were valid for characterizing their response to more complex fluctuations, in which case the assumed insensitivity would be convincingly demonstrated and the aforementioned proposals would go ahead. However, our work revealed that not all modern lamps show a consistent relationship between their gain curve and their behavior in real scenarios. Moreover, the present work clearly challenges the assumed insensitivity of new lighting technologies. The results point to uncertainty in the outcome of increasing the flicker compatibility levels, and difficulties in adapting the IEC flickermeter to a less-sensitive reference lamp.

2. Experimental Setup

This section describes the set of lamps under test (LUTs) and the system used to supply the lamps and to record the illuminance signals.

2.1. Set of LUTs

The main characteristics of the selected LUTs are given in Table 1. We selected a set of commercially available lamps from different manufacturers and using different lighting technologies, including halogen, linear fluorescent (LFL), compact fluorescent (CFL; using electronic or electromagnetic ballast), and light-emitting diode (LED) lamps. The study also included a CFL dimmable lamp because this feature involves additional brightness-control methods that also affect the flicker [12]. The LUTs had different energy efficiency ratings; these were based on European Union energy labeling, which uses classes from the most efficient (A) to the least efficient (G).

2.2. Voltage Generation and Illuminance Recording

Fig. 1 depicts the experimental setup used to generate the supply voltage for the LUTs and to record their illuminance signals. The setup could generate real or analytical voltage signals. The real voltage signals were previously recorded at a sampling rate of 6400 Hz by an acquisition system based on an analog-to-digital (A/D) converter (National Instruments (NI) USB-6281) with 18-bit resolution. The digitized analytical or real signal was converted into an analog signal by a digital-to-analog (D/A) converter (NI USB-6211) at a rate of 6400 Hz. The analog signal was amplified to 230 V by a 7500 Krohn-Hite Amplifier (75 W, from DC to 1 MHz) and a 120/230 V transformer. The output of the transformer was supplied to the LUT, which was enclosed in a white box together with the light sensor, and was connected to a luxmeter (E4-X Hagner Digital Luxmeter). This provided the illuminance signal, $l(t)$, which was digitized by another A/D converter (NI USB-6211) at a rate of 6400 Hz with 16-bit resolution, and then finally stored.

3. Response to Analytical Voltage Fluctuations

The responses of lamps to voltage fluctuations have traditionally been studied by means of their gain curves [8, 10, 13, 14]. A lamp is more sensitive to voltage fluctuations when its gain curve is higher. Each data point on this curve represents the gain factor for a given frequency of the voltage fluctuation, f_m. This parameter assesses the relationship between the relative amplitudes of the illuminance and voltage fluctuations, $\frac{\Delta L}{L}$ and $\frac{\Delta V}{V}$, respectively:

$$G(f_\mathrm{m}) = \frac{\Delta L/L}{\Delta V/V}. \tag{1}$$

The supply voltage of the LUT, when subjected to analytical voltage fluctuations, can be expressed as follows:

$$u(t) = \sqrt{2}A\big(1 + g_\mathrm{m}(t)\big)\cos(\omega_\mathrm{o} t)\ , \tag{2}$$

where $\omega_\mathrm{o} = 2\pi f_\mathrm{o}$ represents the frequency of the mains supply, A represents its Root Main Square (RMS) value, and $g_\mathrm{m}(t)$ represents the fluctuation.

For a sinusoidal voltage fluctuation, $g_{\mathrm{m}}(t)$ consists of a single frequency, f_{m}, of relative amplitude $\frac{\Delta V}{V}$. In this case, the illuminance fluctuation also consists of a single frequency, f_{m}, of relative amplitude $\frac{\Delta L}{L}$. Fig. 2a depicts the gain curve of each LUT, G_{LUT}, normalized to the values corresponding to the reference incandescent lamp, G_{I1}. Each LUT was subjected to 32 sinusoidal fluctuations with f_{m} values ranging from 1 to 32 Hz, with $\frac{\Delta V}{V} = 1\%$, according to (2). The results reveal that the sensitivity of the halogen lamp (H1) is quite close to that of I1 over the whole frequency range, while the rest of the LUTs show reduced sensitivity (relative to I1) over a wide frequency range, from approximately 3 to 25 Hz.

3.1. Sensitivity analysis for rectangular fluctuations

For rectangular voltage fluctuations, which are characterized by an unlimited bandwidth, it is not possible to calculate $\frac{\Delta L}{L}$ for some of the LUTs. Fig. 3 depicts the waveforms of the illuminance fluctuations for the I1 and F1 lamps for a rectangular voltage fluctuation with $f_{\mathrm{m}} = 8$ Hz and $\frac{\Delta V}{V} = 1.5\%$. In the case of I1 (Fig. 3a), the illuminance envelope still consists of a predominant frequency fluctuation that allows the calculation of the relative amplitude, ΔL. However, in the case of F1 (Fig. 3b), the complexity of the waveform does not allow the direct identification of ΔL or the accurate calculation of its gain factor.

An alternative method for studying the responses of the lamps to complex voltage fluctuations should consider all the frequency components of the illuminance fluctuation that affect the flicker [15]. Thus, it would consider the real characteristics of the LUT and provide a closer approximation to the real irritation it produces. Assessment of the flicker severity by means of an illuminance flickermeter meets these requirements.

The IEC 61000-4-15 standard defines the design specifications for a flickermeter based on the voltage supply, according to a physiological model of the lamp–eye–brain chain. Some of the five blocks of the model are based on the performance characteristics of the 60 W incandescent lamp. An illuminance flickermeter would be based on the illuminance rather than the voltage signal, but should otherwise be based on the IEC flickermeter, with modification of the blocks in the IEC model that use the incandescent lamp's response to voltage fluctuations as a reference. An illuminance flickermeter only includes four blocks

(Fig. 4) because the quadratic demodulation (Block 2 of the IEC standard) is eliminated. Moreover, the weighting filter in Block 3 of the IEC standard, corresponding to the lamp–eye response, is modified so that the frequency characteristics of the human eye are only used in Block B. The current work used a highly accurate implementation of an illuminance flickermeter that was described in detail and validated in [16].

The acquisition system depicted in Fig. 1 registered the illuminance of each LUT subjected to rectangular voltage fluctuations, generated according to (2). Each LUT was subjected to 32 fluctuations with f_{m} values from 1 to 32 Hz, corresponding to $\frac{\Delta V}{V}$ values that produced one unit of flicker severity for an incandescent lamp, i.e., $P_{\mathrm{st,I1}} = 1$. The recorded illuminance signals were processed by the illuminance flickermeter, and the corresponding flicker severity values, $P_{\mathrm{st,LUT}}$, were obtained.

Fig. 2b depicts these $P_{\mathrm{st,LUT}}$ values. The results reveal three different behaviors. First, the C1 and L1 lamps exhibit low sensitivities, clearly below that of the incandescent lamp, with results comparable to their corresponding gain curves generated based on sinusoidal voltage fluctuations (Fig. 2a). Second, the sensitivity of lamp H1 is close to, or even higher than, that of the incandescent lamp, with results comparable to the gain curve. Third, the rest of the LUTs show different responses to sinusoidal and rectangular fluctuations. The response of C2 to rectangular fluctuations is higher than the gain curve for the whole frequency range and shows more sensitivity than I1 from 18 Hz onward. The response of F1 to rectangular fluctuations is similar to the gain curve up to 25 Hz; from this frequency onward, the sensitivity of F1 is quite close to that of the incandescent lamp. The response of C3 is also quite similar to the gain curve up to 25 Hz, but from this frequency onward it shows greater sensitivity than I1.

The analysis showed that the behavior of some LUTs was different when supplied with rectangular versus sinusoidal voltage fluctuations. The higher complexity of the rectangular fluctuations produced flickering behavior in some LUTs that differed from their expected responses according to their gain curves. Hence, it is necessary to analyze the responses of the LUTs when they are supplied with real signals, i.e., with fluctuations that are presumably more complex because of their lack of repetitive characteristics.

4. Behavior in Real Scenarios

We analyzed the response of each LUT to voltage signals registered at four different locations of the Low Voltage (LV) network (230 V/50 Hz) in the north of Spain. The locations were selected based on features such as the population, type of disturbing loads, and level of flicker severity.

4.1. Description of the sites

Fig. 5 depicts the evolution of the P_{st} and P_{lt} values for the real voltage signals at each site over approximately one week, as well as their 99^{th} percentiles, assessed by means of the IEC flickermeter [5]. Additionally, the figures include the percentage of time, T_{TH}, for which both parameters exceed the irritability threshold ($P_{\text{st}} = 1$, $P_{\text{lt}} = 1$). The P_{lt} values were calculated using a time interval of two hours, i.e., 12 short time intervals. A P_{lt} value was calculated as the cubic average of 12 consecutive P_{st} values. Each new P_{lt} value was obtained with the 11 most recent P_{st} values used in the calculation of the previous P_{lt} value and the next new P_{st} value. Following this procedure, one P_{lt} value for each P_{st} value was obtained. A brief description of each site is detailed next.

- Site a (S_a): A metropolitan area of 900,000 inhabitants with relevant industrial activity, including steel mills working with arc furnaces. This site did not present excessive flicker severity levels: $P_{\text{st},99} = 1.21$ and $P_{\text{lt},99} = 0.93$, being close to the irritability threshold, with only 3.8% of the P_{st} values exceeding this limit and all the P_{lt} values being below it (Fig. 5a).

- Site b (S_b): A tourist destination of 100,000 inhabitants (residents and visitors) during the holiday period. This site is located far from big industrial loads. In this case, the flicker severity values remained above the irritability threshold: $P_{\text{st},99} = 1.74$ and $P_{\text{lt},99} = 1.49$. The flicker severity values exceeded the limit 67% of the time for P_{st} and 86.6% of the time for P_{lt} (Fig. 5b).

- Site c (S_c): A small town of 15,000 inhabitants located in a steel industry area, predominantly with installations equipped with arc furnaces. The duty cycle of these industries can be easily identified in Fig. 5c. The flicker severity values were clearly above the irritability threshold: $P_{\mathrm{st},99} = 2.06$ and $P_{\mathrm{lt},99} = 1.63$. Despite the long inactivity period of the arc furnaces, the P_{lt} value is above the irritability threshold 68.8% of the time (Fig. 5c).

- Site d ($\mathrm{S_d}$): A rural, sparsely populated area near a steel industry area where there are arc furnaces that follow a continuous duty cycle, with short periods of inactivity. Flicker severity values were clearly above the irritability threshold: $P_{\mathrm{st},99} = 2.29$ and $P_{\mathrm{lt},99} = 1.92$, with $T_{\mathrm{TH},P_{\mathrm{lt}}} = 95.3\%$ (Fig. 5d).

4.2. Complexity of the real voltage signals

We studied the temporal and spectral uniformity of the real voltage signals. Fig. 6a shows the temporal evolution of the RMS value for a representative time series of 10 min from $\mathrm{S_c}$. Fig. 6b depicts the power spectral density (PSD) obtained using the Welch estimator for the same 10 min interval. The PSD values were normalized to the amplitude of the 50 Hz component. This example shows the large number of harmonic and interharmonic components present in the real voltage signals. Furthermore, the evolution of the RMS values reflected irregular patterns that contrast with the uniformity of the analytical fluctuations.

To extend these observations to the complete set of recorded voltages, a numerical study of their complexity is presented. The spectral entropy (SE) was used to estimate the uniformity of a certain frequency distribution [17, 18]. According to this method, a sinusoidal function with a spectral distribution that is concentrated around a single component corresponds to the lower limit of SE, whereas white Gaussian noise corresponds to the upper limit of SE. The calculation of SE is based on PSD estimation over an interval of duration t_{w}. The PSD is then normalized, generating a probability-like distribution, P_{i}. The estimation of the entropy was obtained by applying information theory to a discrete probability distribution [19]:

$$\mathrm{SE} = \sum_{i} P_{\mathrm{i}} \cdot log_2\left(\tfrac{1}{P_{\mathrm{i}}}\right). \tag{3}$$

The envelope of each recorded voltage was calculated as specified in blocks 2 and 3 of the

IEC standard [5]. The voltage was demodulated by means of a squaring multiplier. Then, two filters were applied to complete the demodulation process: a 1st-order high-pass filter (3 dB cutoff frequency $f_{\mathrm{co}} = 0.05$ Hz) and a 6th-order low-pass Butterworth filter (3 dB cutoff frequency $f_{\mathrm{co}} = 35$ Hz). The SE of each envelope was calculated for different time intervals over the study period, each lasting $t_{\mathrm{w}} = 60$ s, thus yielding a sequence of discrete SE values. Table 2 shows the mean and standard deviation values of the sequences for each site, plus the mean and standard deviation of SE values corresponding to both sinusoidal and rectangular fluctuations with $\frac{\Delta V}{V} = 1\%$ and $f_{\mathrm{m}} = 10$ Hz, generated according to (2), plus the SE parameters of a random noise sequence.

The sinusoidal fluctuations produce negligible SE values; the random noise produces significant SE values; and the rectangular fluctuations produce SE values clearly closer to the lower limit than to the upper one. The mean SE values obtained for the envelopes of real voltage signals were considerably higher than the mean SE values for the rectangular fluctuations. The standard deviation of the SE was also high at every site, revealing a significant dispersion in the temporal evolution of the spectral content of these signals. The results reveal the higher complexity of real voltages compared with analytical voltage fluctuations, confirming the need to analyze the specific behavior of the LUTs when supplied with real voltage signals.

4.3. LUTs' response to real voltage signals

The LUTs were supplied with the recorded real voltages and the illuminance signals were registered by means of the system shown in Fig. 1. The P_{st} and P_{lt} values produced by each LUT were calculated using the illuminance flickermeter. Taking into account the duration of the recordings and the number of LUTs, the time required to perform the experiment was reduced by selecting a shorter study period of three days for each site. In Fig. 5, the selected time intervals are indicated with gray areas.

Fig. 7 depicts the temporal evolution of the P_{lt} values obtained for the LUTs at each site. Based on the cumulative probability function of the P_{lt} sequences, the box-plot for each LUT is also represented. In each box-plot, the horizontal line represents the median of the distribution, while the bottom and top of the box indicate the 25^{th} and 75^{th} percentiles, respectively, showing the dispersion of the represented data; concentric circles represent the minimum value and the 99^{th} percentile. The three-day period captured real situations with long periods of high flicker severity. This feature produced box-plots of I1 with distributions biased toward the highest percentiles in the case of the sites $\mathrm{S_a}$, $\mathrm{S_b}$, and $\mathrm{S_d}$. At $\mathrm{S_c}$, the periods of inactivity of the arc furnaces produced a more dispersed distribution. Additionally, Table 3 shows the temporal percentages T_{S} for each LUT, representing the P_{lt} values that simultaneously exceed the irritability threshold ($P_{\mathrm{lt}} = 1$) and show a sensitivity level similar to, or even higher than, that of the incandescent lamp ($P_{\mathrm{lt,LUT}} \geq 0.9 \cdot P_{\mathrm{lt,I1}}$).

Comparing the $P_{\mathrm{lt,99}}$ values of I1 (Fig. 7) with those obtained with the IEC flickermeter for each selected three-day period of real voltages ($P_{\mathrm{lt,99}}(\mathrm{S_a}) = 0.9$, $P_{\mathrm{lt,99}}(\mathrm{S_b}) = 1.3$, $P_{\mathrm{lt,99}}(\mathrm{S_c}) = 1.5$, $P_{\mathrm{lt,99}}(\mathrm{S_d}) = 1.8$), identical results were obtained. These consistent results confirm that the lamp model included in the specification of the IEC flickermeter properly reflects the behavior of the incandescent lamp.

For the rest of the LUTs, however, the results for real signals reveal three different behaviors. First, the C1 and L1 lamps show low responses, clearly below those of I1, for every site. C1 shows the highest response at $\mathrm{S_b}$, where $P_{\mathrm{lt,99}}(\mathrm{C1}, \mathrm{S_b}) = 0.8$, whereas $P_{\mathrm{lt,99}}(\mathrm{I1}, \mathrm{S_b}) = 1.3$. The most sensitive behavior of L1 occurs at $\mathrm{S_d}$, where $P_{\mathrm{lt,99}}(\mathrm{L1}, \mathrm{S_d}) = 0.6$, whereas $P_{\mathrm{lt,99}}(\mathrm{I1}, \mathrm{S_d}) = 1.8$. Neither lamp ever produces a P_{lt} value simultaneously above the irritability threshold and above the incandescent lamp at any site, $T_{\mathrm{S}}(\mathrm{C1}) = T_{\mathrm{S}}(\mathrm{L1}) = 0\%$. This behavior is compatible with the results from the experiments with analytical fluctuations.

Second, the responses of the H1 and C3 lamps were closer to, or even higher than, those of the incandescent lamp. The H1 and I1 lamps show almost identical P_{lt} distributions at every site, with I1 slightly above H1. According to Fig. 7h, the most sensitive behavior of H1 occurs at $\mathrm{S_d}$, where $P_{\mathrm{lt,99}}(\mathrm{H1}, \mathrm{S_d}) = 1.7$ and $T_{\mathrm{S}}(\mathrm{H1}, \mathrm{S_d}) = 92.6\%$, whereas $P_{\mathrm{lt,99}}(\mathrm{I1}, \mathrm{S_d}) = 1.8$. This behavior is in agreement with the results from the experiments with analytical fluctuations. The response of lamp C3 was slightly lower than that of I1 at $\mathrm{S_a}$, but C3 presented higher values at $\mathrm{S_b}$, $\mathrm{S_c}$, and $\mathrm{S_d}$; specifically, at $\mathrm{S_d}$, $P_{\mathrm{lt,99}}(\mathrm{C3}, \mathrm{S_d}) = 2.0$ and $T_{\mathrm{S}}(\mathrm{C3}, \mathrm{S4}) = 92.3\%$. It should be noted that the behavior of C3 was quite inconsistent with the results from the experiments with analytical fluctuations; according to the analytical experiments (Fig. 2), C3 is less sensitive than I1 over a wide range of f_m values for both sinusoidal and rectangular fluctuations.

Third, the results for C2 and F1 show inconsistent behavior across the different sites. F1 presents a lower response than I1 at $\mathrm{S_a}$, $\mathrm{S_b}$, and $\mathrm{S_d}$ (Fig. 7e,f,h). This behavior is in agreement with the results from the experiments with analytical fluctuations. However, F1 shows unexpected results at $\mathrm{S_c}$, where it becomes more sensitive than I1. According to Fig. 7g, $P_{\mathrm{lt},99}(\mathrm{F1}, \mathrm{S_c}) = 2.1$, whereas $P_{\mathrm{lt},99}(\mathrm{I1}, \mathrm{S_c}) = 1.5$. As detailed in Table 3, at $\mathrm{S_c}$, F1 has a T_S percentage above 60%, revealing an important inconsistency with the experiments with analytical fluctuations, in which the sensitivity of F1 is clearly lower than that of I1 for a wide range of fluctuation frequencies. The lamp C2 shows a lower response than I1 at $\mathrm{S_b}$ and $\mathrm{S_d}$, and this behavior is compatible with the results from the experiments with analytical fluctuations. However, at $\mathrm{S_a}$ and $\mathrm{S_c}$, the response of C2 is quite similar to, or even higher than, that of I1. In particular, at $\mathrm{S_c}$, $P_{\mathrm{lt},99}(\mathrm{C2}, \mathrm{S_c}) = 2.0$, whereas $P_{\mathrm{lt},99}(\mathrm{I1}, \mathrm{S_c}) = 1.5$ and $T_\mathrm{S}(\mathrm{C2}, \mathrm{S_c}) = 64.3\%$. As in the case of F1, the response of C2 at these sites is not in agreement with its behavior when subjected to analytical fluctuations; in the latter case, it shows low sensitivity over a wide range of fluctuation frequencies.

The analysis with real signals thus provided remarkable results. Some LUTs showed considerably sensitive behavior, with heavy dependence on the type of lamp technology. Other LUTs showed nonuniform responses across the different sites. The results also showed discrepancies in the behavior of some LUTs when subjected to analytical fluctuations versus real signals. These factors reveal the unpredictable behavior of some modern lamps when the input voltages are complex.

5. Discussion and Conclusions

In the past ten years, different studies have analyzed modern lamps' sensitivities to voltage fluctuations. Two of them [8, 13] suggest that some modern lamps are less sensitive than incandescent lamps. They used the gain curves of the studied lamps when subjected to sinusoidal and rectangular fluctuations. However, the results from [13] suggest some peculiarities, such as the higher sensitivity of some of the analyzed LED lamps compared with incandescent lamps. Other works have analyzed the response of modern lamps to sinusoidal and rectangular voltage fluctuations by means of an illuminance flickermeter [20, 21]. The CFL lamps analyzed in [20] and the LED lamps analyzed in [21] showed low sensitivity to the applied voltage fluctuations. However, the results obtained when lighting technologies are subjected to voltages disturbed by interharmonic components are remarkable [14, 20, 22]. Using the gain curves or an illuminance flickermeter, these works show that CFL and LED lamps are sensitive to interharmonic components above 100 Hz, in contrast to the immunity shown by the incandescent lamps.

The common conclusions drawn from these studies have prompted general agreement about the low sensitivity of modern lamps to voltage fluctuations. During the past few years, several works have explored the consequences of that assumption. Firstly, from 2007 onward, some works revealed the difficulty in explaining the existence, at different sites, of flicker levels far exceeding the $P_{\mathrm{st}} = 1$ threshold but which did not always result in the expected complaints from network users [23, 24]. To explain this phenomenon, a report from the International Council on Large Electric Systems (CIGRE) C4.108 working group suggested that the inconsistency could be attributable to the low sensitivity of modern lighting to voltage fluctuations [7]. The conclusions of the report proposed the adaptation of the IEC flickermeter to a new reference lamp with lower sensitivity in order to obtain more realistic measurements of flickering by modern lamps. In 2010, the working group C4.111 of CIGRE was established to study two alternatives: changing the reference lamp of the IEC standard, or increasing the established compatibility levels for voltage fluctuations [9].

The objective of the current work was to analyze in depth the behavior of modern lighting technologies when subjected to voltage fluctuations. The work presents an analysis of the spectral complexity of the voltage fluctuations used. The work assesses the responses of a set of modern lamps to analytical fluctuations of low complexity and—for the first time in the literature—to real voltage signals of high complexity. The results were quite unexpected and remarkable.

First, the results clearly challenge the assumed insensitivity of new lighting technologies. Some of these new lighting technologies showed low sensitivity to voltage fluctuations in real scenarios. However, this cannot be generalized, because the results obtained for other lamps that have considerable market share [25] showed higher sensitivity than incandescent lamps. This fact undermines the explanation previously given for the absence of complaints in areas with high voltage flicker levels. Furthermore, the existence of some modern lamps with sensitive behavior in real scenarios makes the alternative of increasing the compatibility levels unfeasible.

Second, our results, in accordance with previous works [13, 14, 20, 22], indicate that modern lamps are not of uniform sensitivity. Their sensitivity seems to depend on the lighting technology, the complexity of the input voltage fluctuations, and the site where the lamp is used. These facts complicate the possibility of changing the reference lamp used in the IEC standard. The current standard uses the gain curve of the incandescent lamp as a linear model. The selection of a new reference lamp would require modification of the lamp model by including the gain curve of the new selected lamp, assuming linear behavior. Our work showed that the flicker severity values measured by the illuminance flickermeter for the incandescent lamp were almost identical to the values measured by the IEC flickermeter, confirming the adequacy of the current linear model for incandescent lamps. However, our work also demonstrates that the gain curves of some modern lamps do not represent their behavior when they are supplied with real signals; instead, they exhibit nonlinear behaviors. Hence, the selection of a new reference lamp would also require the creation of a nonlinear lamp model [26].

A possible solution could be to incorporate immunity to voltage fluctuations into the design process of new lighting technologies, thus achieving better control over lamp flickering. New lighting technologies would have to be designed with lower responses to voltage fluctuations than those typical of incandescent lamps. The responsibility for ensuring that new lamps had low sensitivity would fall on the lamp manufacturers. However, it is important to consider again the differences in the behavior of some modern lamps when subjected to analytical fluctuations versus real signals, which would complicate the design of any immunity protocol for new lamps.

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Figure Captions

Figure 1	Diagram of the voltage generation and illuminance recording processes.
Figure 2	LUT sensitivity curves. (a) Gain curves for sinusoidal voltage fluctuations and (b) P_{st} values for rectangular voltage fluctuations.
Figure 3	Waveform of the illuminance fluctuation for a rectangular voltage fluctuation. (a) I1 lamp and (b) F1 lamp.
Figure 4	Functional diagram of the illuminance flickermeter.
Figure 5	Time evolution of P_{st} and P_{lt} values for the real voltage signals at each site; (a) $\mathrm{S_a}$, (b) $\mathrm{S_b}$, (c) $\mathrm{S_c}$ and (d) $\mathrm{S_d}$.
Figure 6	Real voltage signal at $\mathrm{S_c}$ site. (a) Temporal evolution of the voltage fluctuation and (b) power spectral density by Welch estimator.
Figure 7	P_{lt} values for each LUT at the selected sites. (a,b,c,d) Time evolution and (e,f,g,h) box-plots, corresponding to $\mathrm{S_a}$, $\mathrm{S_b}$, $\mathrm{S_c}$ and $\mathrm{S_d}$.

Table Titles

Table 1	Set of lamps under test (LUTs).
Table 2	Spectral Entropy of the analyzed signals.
Table 3	T_{S}: percentage of $P_{\mathrm{lt,LUT}}$ values exceeding the unit and simultaneously the 90% of the $P_{\mathrm{lt,I1}}$ values.

Figure 1

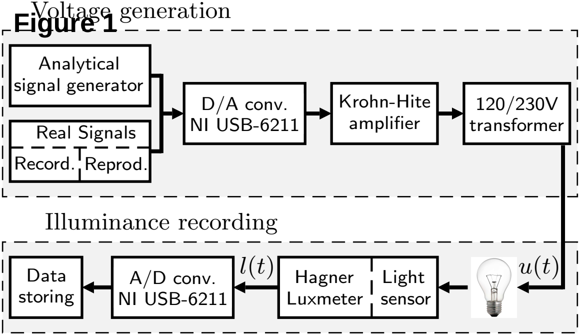
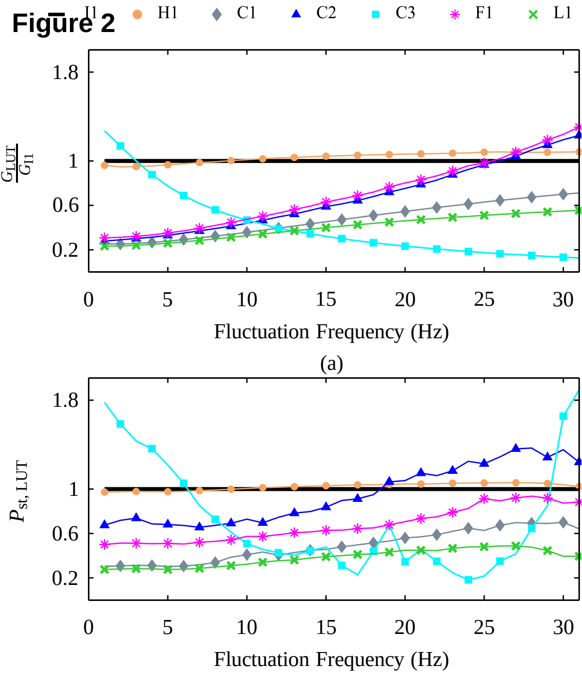

Voltage generation
Analytical signal generator
Real Signals
Record.
Reprod.
D/A conv. NI USB-6211
Krohn-Hite amplifier
120/230V transformer
Illuminance recording
$u(t)$
Light sensor
Hagner Luxmeter
$l(t)$
A/D conv. NI USB-6211
Data storing

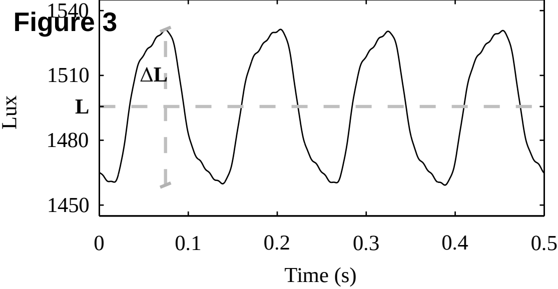
Figure 2


I1
H1
C1
C2
C3
F1
L1
$\frac{G_{\mathrm{LUT}}}{G_{\mathrm{I1}}}$
1.8
1
0.6
0.2
0
5
10
15
20
25
30
Fluctuation Frequency (Hz)
$P_{\mathrm{st,\,LUT}}$
1.8
1
0.6
0.2
0
5
10
15
20
25
30
Fluctuation Frequency (Hz)

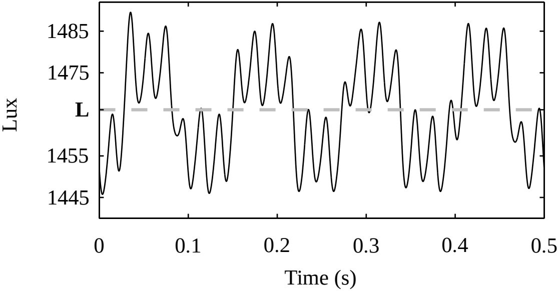
(a)

(b)

Figure 3

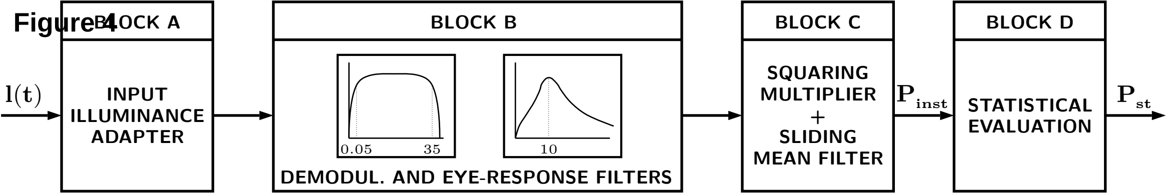

1540
1510
1480
1450
Lux
L
ΔL
0
0.1
0.2
0.3
0.4
0.5
Time (s)

(a)


1485
1475
1455
1445
Lux
L
0
0.1
0.2
0.3
0.4
0.5
Time (s)

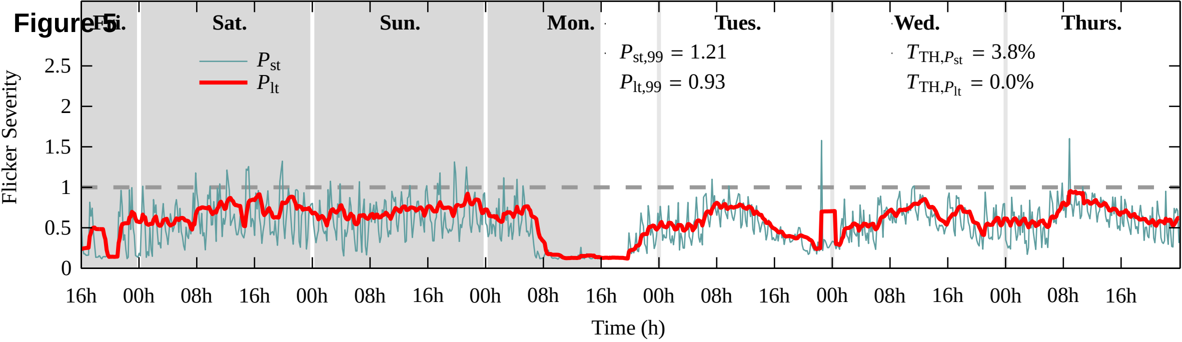
(b)

Figure 4

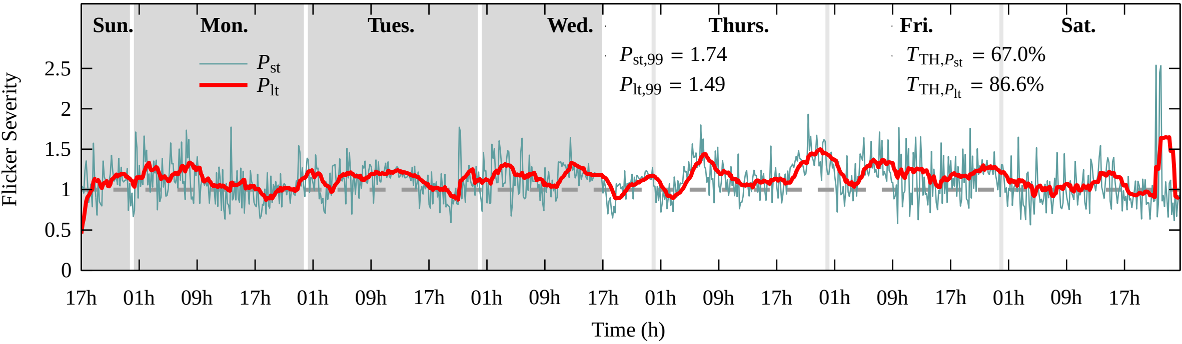


$l(t)$
BLOCK A
INPUT ILLUMINANCE ADAPTER
BLOCK B
0.05
35
10
DEMODUL. AND EYE-RESPONSE FILTERS
BLOCK C
SQUARING MULTIPLIER + SLIDING MEAN FILTER
P_{inst}
BLOCK D
STATISTICAL EVALUATION
P_{st}

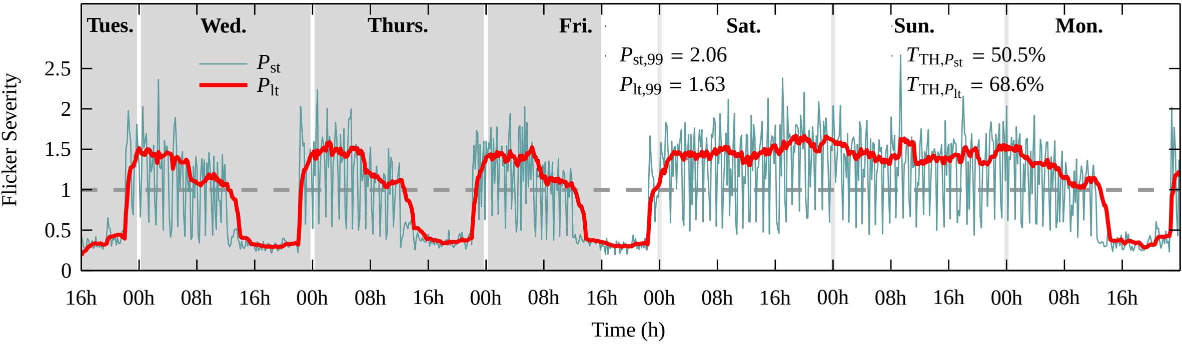
Figure 5



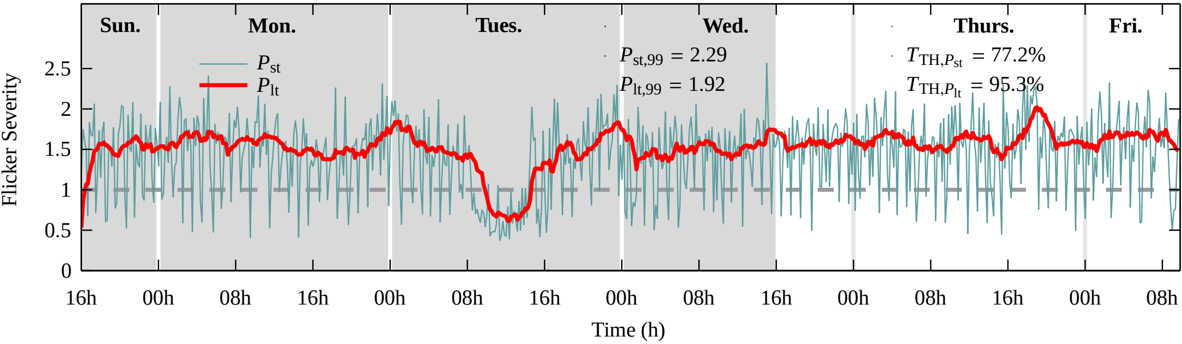
(a)



(b)

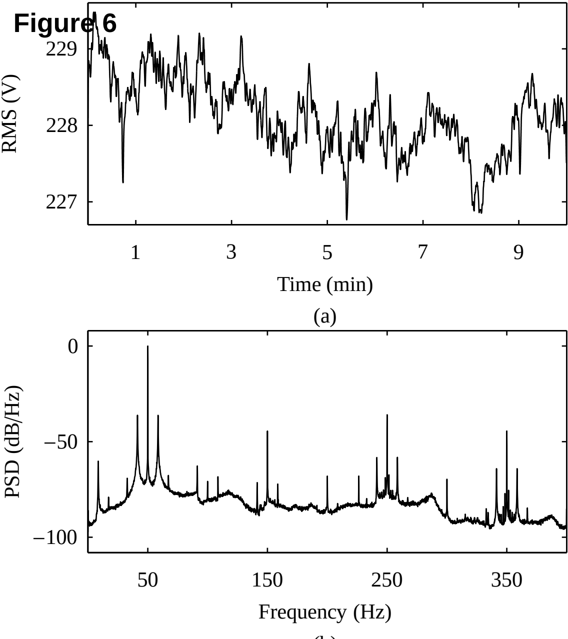


(c)



(d)

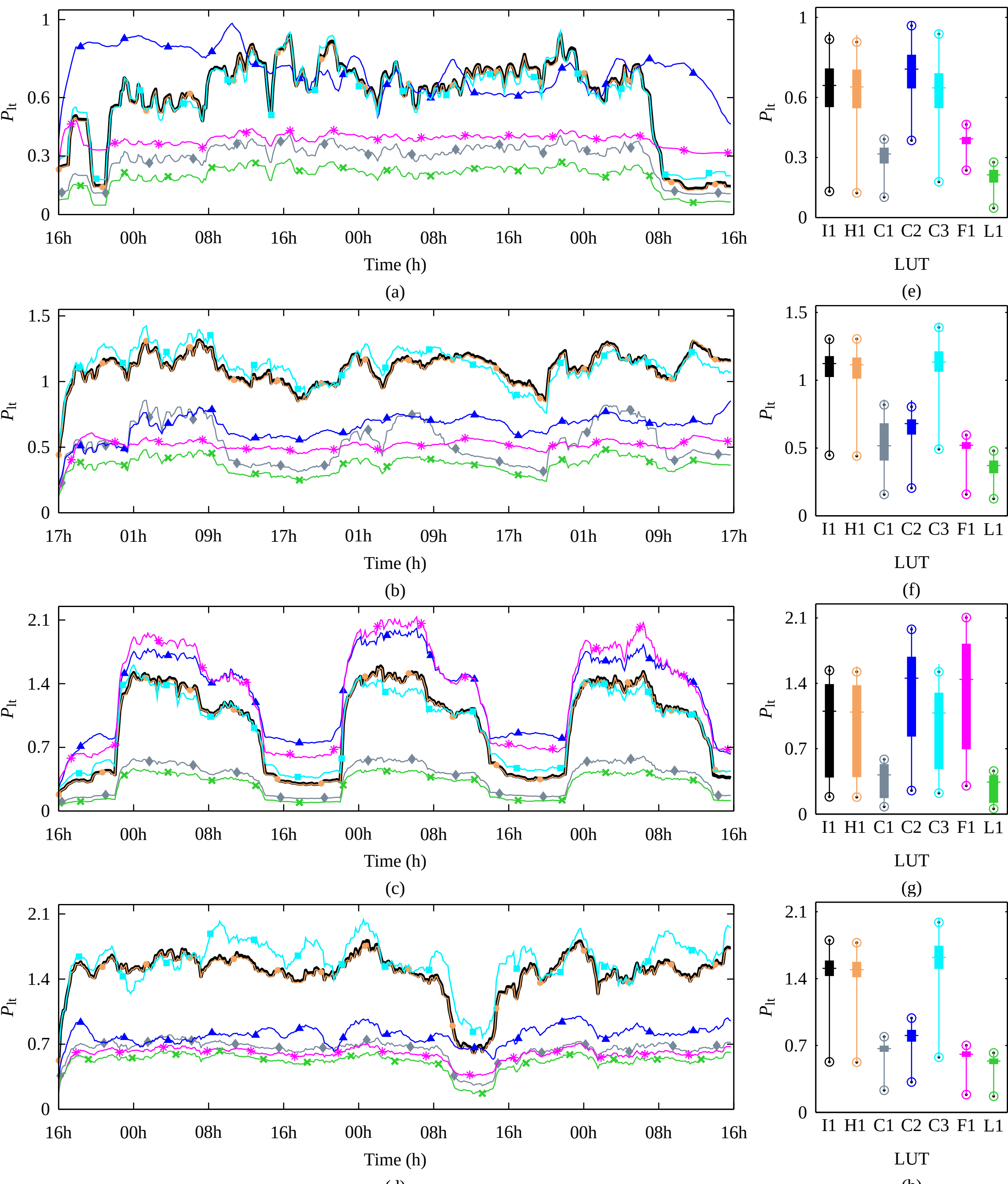
Figure 6


229
228
227
RMS (V)
1
3
5
7
9
Time (min)
0
−50
−100
PSD (dB/Hz)
50
150
250
350
Frequency (Hz)

(a)

(b)

Figure 7



(a) (e)

(b) (f)

(c) (g)

(d) (h)

Table 1

Id.	Lamp Technology	Power[a] (W)	Lum Flux (Lumen)	Energy Efficiency Class	Branch (Model)
I1	Incandescent	60	850	E	Philips
H1	Halogen	42	630	C	Lexman
C1[b]	CFL	23	1380	A	Lexman (EU23W)
C2[c]	CFL	18	1050	B	General Electric (Biax F18DBX)
F1[c]	LFL	18	1050	B	Sylvania (F18W/54-765-T8)
L1	LED	12	650	A	Osram (Parathom Classic A60)
C3[b,d]	CFL	12	600	A	Philips (Softone)

[a] 230 V / 50 Hz

[b] Electronic ballast

[c] Electromagnetic ballast

[d] Dimmable lamp

Table 2

Sim.	Rect.	Rand. Noise	S_a	S_b	S_c	S_d
0.03[a]	0.41	7.34 ± 0.01[b]	4.67 ± 1.21	4.18 ± 1.02	4.83 ± 0.89	4.85 ± 1.04

[a] Mean value of the SE

[b] Standard deviation of the SE

Table 3

	H1	C1	C2	C3	F1	L1
S_a	0	0	0	0	0	0
S_b	79.1	0	0	84.5	0	0
S_c	58.2	0	64.3	51.27	63.6	0
S_d	92.6	0	0	92.3	0	0